doi: 10.14355/fiee.2016.05.009

A Revised Correlation on Downstream Temperature Distribution of Fire-Induced Flow with Mechanical Longitudinal Ventilation

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Abstract

To evaluate the stability of smoke stratification and fire evacuation effectively, the temperature distribution downstream the fire beneath the ceiling of tunnels with mechanical longitudinal ventilation needs to be estimated. Based on Li model, a revised correlation is proposed by concerning the effects of the mechanical longitudinal ventilation velocity and the width of the tunnel. Ten full-scale field test data in three real tunnels from Hu et al. are employed to correlate the revised correlation. The applicability of the new revised model is validated by comparing with the field test data and previous models. Results indicate that the new model can agree with the field test data well. The Mean Absolute Percentage Error (MAPE) of the revised model is found to be 19.99%. Great improvement of the prediction accuracy is achieved as compared with the previous models.

Keywords

Tunnel Fire; Revised Correlation; Maximum Temperature Distribution; Mechanical Longitudinal Ventilation

Introduction

To provide effective fire protection, there is a need for better understanding smoke spreading in tunnels [1]. When the fire smoke spreads along a tunnel, temperature decay will occur along the tunnel due to the heat loss to the ceiling [2]. As the buoyancy force is weaker than the inertial force of the longitudinal ventilation air flow at a distance, the stratification of smoke will be lost [3]. So, knowing the smoke temperature along the tunnel downstream the fire is very important for evaluation of the stability of the smoke stratification and fire evacuation effectively.

A correlation for the temperature distribution was given by Delichatsios [4],

$$\frac{\Delta T}{\Delta T_{\max}}\left(\frac{W}{2H}\right)^{1/3} = 0.49\exp\{-6.67St\frac{x}{H}\left(\frac{W}{2H}\right)^{1/3}\} \tag{1}$$

Where ΔT is excess temperature between T and T0, °C; ΔT_{max} is excess temperature between T and maximum temperature T_{max}, °C; T is smoke temperature, °C; T0 is ambient temperature, °C; W is tunnel width, m; H is tunnel height, m; St is Stanton number; x is distance from the fire, m.

Another correlation was proposed by Bailey et al. [5] as

$$\Delta T = \Delta T_0\left(\frac{1}{2}\right)^{x/16.7} \tag{2}$$

Based on the maximum temperature model of Kurioka et al. [6] and the maximum temperature equation of Li et al. [7], Hu et al [8] proposed a modified empirical correlation by considering tunnel slope. It is expressed as

$$\frac{\Delta T_x}{\Delta T_{max}} = e^{-(1+0.09\beta)Kx} \tag{3}$$

Where β is percentage of the tunnel slope; K is exponential decay coefficient. According to the study of Lee and Ryou [9], above correlations could not correlate the temperature distribution with various cross-section aspect ratios. So, a simple correlation was derived for the temperature distribution of the the fire-induced flow along naturally ventilated tunnels by Li et al. [10].

$$\frac{\Delta T}{\Delta T_{ref}} = \exp\left[-St \cdot \frac{x - x_{ref}}{d}\right] \tag{4}$$

Where xref is reference position, m; d is hydraulic diameter of the tunnel, m. According to the numerical results by Li et al. [10], the Stanton number can be obtained. For tunnels with aspect ratio greater than or equal to 1.0, the Stanton number is 0.00733. For tunnels with aspect ratio smaller than 1.0, the Stanton number is 0.00406 (Aspect ratio of the tunnel cross section is tunnel height/tunnel width).

Recently, a correlation of the fire flow temperature along mechanically ventilated tunnels is proposed by Li et al. [11] based on Eq. (5).

$$\frac{\Delta T}{\Delta T_{max}} = \begin{cases} \exp[-0.0086(x - x_{max})/d], 0 < (x - x_{max})/d \le 50 \\ 3.5\left[(x - x_{max})/d\right]^{-0.43}, 50 < (x - x_{max})/d \end{cases} \tag{5}$$

Some studies [2, 10] indicate that longitudinal ventilation velocity has a major influence on the temperature distribution downstream the tunnel.

Based on theoretical analysis by Li et al. [10] and experimental studies by Hu et al. [2], this paper proposes a new revised model to correlate the temperature distribution downstream the tunnel fire with mechanical ventilation. The applicability of the new revised model is validated by comparing with the experiment work [2] and previous models [4, 5, 10, 11].

Theoretical Analysis

For rectangular tunnel, the correlation of the temperature decay with mechanical ventilation is [11]

$$\frac{\Delta T}{\Delta T_{ref}} = \exp[-\frac{h_c}{\rho C_p u} \cdot \left(2\phi + 20.3\phi^{-1}\right)\left(x - x_{ref}\right)/H] \tag{6}$$

Where ΔTref is excess temperature between Tref and T0, °C; hc is heat transfer coefficient, W m-2°C-1; ϱ is density of the air, kg m-3; Cp is specific heat, J·kg-1·°C-1; u is longitudinal ventilation velocity, m s-1; ϕ is aspect ratio of the tunnel cross section, ϕ=H/W.

For arch tunnel, the correlation of the temperature decay with mechanical ventilation is [10]

$$\frac{\Delta T}{\Delta T_{ref}} = \exp[-\frac{h_c}{\rho C_p u} \cdot \left(2 + 20.3(\phi - 0.11)^{-2}\right)\left(x - x_{ref}\right)/W] \tag{7}$$

As arch tunnel is the common type, the paper mainly investigates the Eq. (7). Thus, for mechanically ventilated tunnels, Eq. (7) is expressed as

$$\frac{\Delta T}{\Delta T_{ref}} = \exp\left(-\frac{c}{a \times V + b} \times \frac{x - x_{ref}}{W}\right) \tag{8}$$

Where $$\frac{\Delta T}{\Delta T_{ref}} = \frac{T_x - T_0}{T_{ref} - T_0} \tag{9}$$

The excess temperature is the temperature difference between T and T0. The smoke temperature Tx is measured by the thermocouple and the thermal resistors at distance x from the fire; and Tref is the temperature at the reference position downstream the fire as shown in Figure 1.

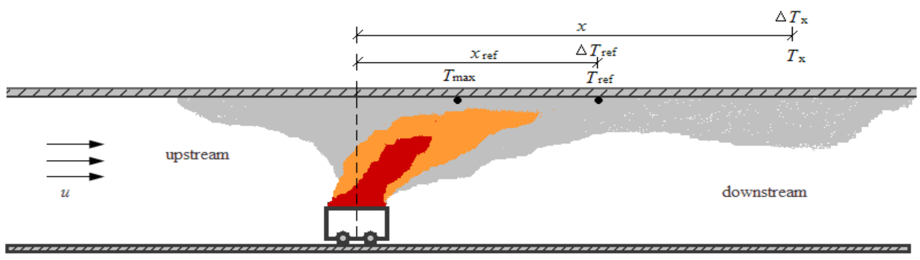

FIG. 1 SCHEMATIC DIAGRAM OF SMOKE MOVEMENT IN A TUNNEL FIRE

Experimental Examination

Test data by Hu et al. [2] are used to examine the revised correlations. The tests were carried out in three full-scale road tunnels by Hu et al..

Three fire tests were conducted in YangZong Road Tunnel and there were three fire tests and four fire tests which were conducted in DaFengYaKou Road Tunnel and YuanJiang1# Road tunnel respectively. Ten fire tests were summarized in Table 1.

TABLE 1 SUMMARY OF THE FULL-SCALE TESTS USED BY HU ET AL.[2]

Tunnel name	Test number	Pool size	Fuel(liters used)	Heat release rates (MW)	Height of the pool fire source above the floor(m)	Longitudinal Ventilation velocity(m s-1)	Ambient temperature(°C)
YangZongTunnel	Test 1	1 m2	Gasoline/12	1.8	0.2	2.5	20
	Test 2	2 m2	Diesel oil/30	3.2	0.2	0.5	20
	Test 3	2 m2	Diesel oil/9 +Gasoline /8	2.5	0.2	4.5	20
DaFengYaKou Tunnel	Test 4	1 m2	Gasoline /20	1.8	1.7	0.5	17.5
	Test 5	1 m2	Gasoline /20	1.8	0.2	1.9	17.5
	Test 6	2 m2	Gasoline /40	3.2	0.2	0.8	17.5
YuanJiang 1# tunnel	Test 7	1 m2	Gasoline /20	1.8	1.7	1.0	21.5
	Test 8	1 m2	Gasoline /15	1.8	0.2	0.6	22
	Test 9	2m2	Gasoline /30	3.2	0.2	0.5	25
	Test 10	2 m2	Gasoline /30	3.2	0.2	0.9	24

Revised Model Correlation and Validation

Correlation

Test data in Table 1 are used to correlate the Eq. (8). The reference positions are +20m or +60m from the fire source. The relevant parameters concluded from the fitting to Eq. (8) are that a=-1.05, b=3.81 and c=0.2, with a correlation coefficient R2 =0.9737. The new correlation is expressed as

$$\frac{\Delta T}{\Delta T_{ref}} = \exp\left(-\frac{0.2}{-1.05\times V+3.81}\times\frac{x-x_{ref}}{W}\right) \tag{10}$$

Validation

Comparison of the new model with test data is presented in Figure 2. It is shown that Eq. (10) can reasonably correlate the temperature distribution for all test data involved.

As shown in Figure 2, approximately 87% of the predicted excess temperature is consistent with the experimental data within a relative deviation of $\pm 15\%$. The revised correlation presents a good agreement with the experimental data.

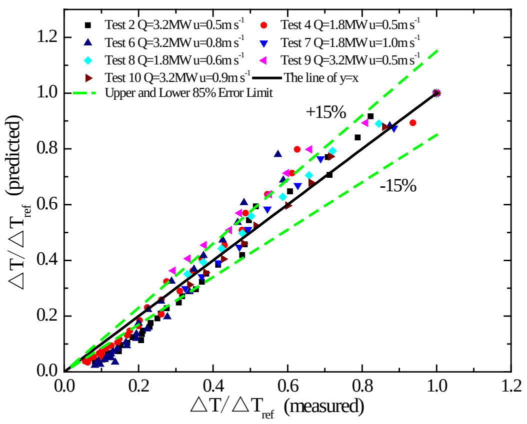

FIG. 2 VALIDATED BY THE TEST DATA

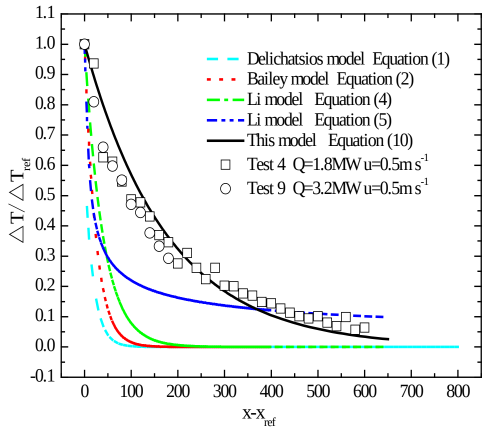

FIG. 3 COMPARISON WITH OTHER MODELS

The correlation is further verified by comparing the predicted excess temperature with other models, Delichatsios model, Bailey model, Li model and the new revised model. It is shown in Figure 3 that the temperature decay for Delichatsios model, Bailey model and Li model is much faster than the new revised model.

The parameter of Mean Absolute Percentage Error (MAPE) is used to evaluate the accuracy of the revised model with the previous models. MAPE is the mean absolute percentage error in prediction. It indicates the forecast accuracy of a model. The equation of MAPE is expressed as

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Y_i - \hat{Y}_i}{Y_i}\right| \times 100\% \tag{11}$$

The results of the comparison are shown in Figure 4. The new revised model presents an agreeable MAPE value of 19.99%. Great improvement is clearly indicated by comparing with the other models.

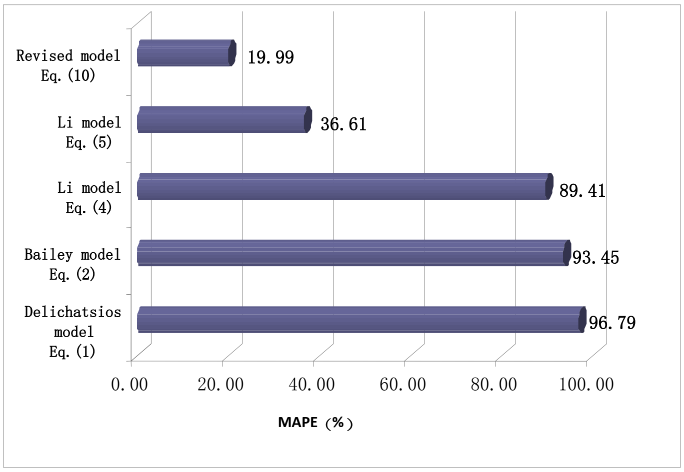

FIG. 4 COMPARISON OF MAPE WITH OTHER MODELS

Conclusions

Base on Li model and test data conducted by Hu et al., a revised correlation of temperature distribution along the tunnel with mechanical ventilation including both the tunnel width and longitudinal ventilation velocity is further developed. The MAPE of the revised new model is 19.99%. Great improvement is found by comparing with the previous models. The results indicate that the revised model can be utilized to predict the temperature distribution of the fire with acceptable accuracy.

ACKNOWLEDGEMENT

This work was supported by the National Science Foundation of China under Grant No. 51178015.

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